# APPENDIX II

# CONSTRAINED-ENVELOPE DIGITAL-COMMUNICATIONS TRANSMISSION SYSTEM AND METHOD THEREFOR

## TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field of digital communications. More specifically, the present invention relates to the field of constrained-envelope digital transmitter circuits.

## BACKGROUND OF THE INVENTION

A wireless digital communications system should ideally refrain from using any portion of the frequency spectrum beyond that actually required for communications. Such a maximally efficient use of the frequency spectrum would allow the greatest number of communications channels per given spectrum. In the real-world, however, some spectral regrowth (i.e., increase in spectral bandwidth) is inevitable due to imperfect signal amplification.

In wireless communication systems various methodologies have been used to minimize spectral regrowth. Some conventional methodologies utilize complex digital signal processing algorithms to alter a digitally modulated transmission signal in some manner conducive to minimal spectral regrowth. Such complex algorithmic methodologies are well suited to low-throughput applications, i.e., those less than 0.5 Mbps (megabits per second), such as transmission of vocoder or other audio data. This is because the low throughput rate allows sufficient time between symbols for the processor to perform extensive and often repetitive calculations to effect the required signal modification. Unfortunately, high-throughput applications, i.e., those greater than 0.5 Mbps, such as the transmission of high-speed video data, cannot use complex processing algorithms because the processing power required to process the higher data rate is impractical.

A digital signal processing methodology may be used with the transmission of burst signals. With burst transmissions, the interstitial time between bursts may be used to perform the necessary complex computations based upon an entire burst. This methodology is not practical when continuous (as opposed to burst) transmission is used.

A conventional form of post-modulation pulse shaping to minimize spectral bandwidth utilizes some form of Nyquist-type filtration, such as Nyquist, root-Nyquist, raised cosine-rolloff etc. Nyquist-type filters are desirable as they provide a nearly ideal spectrally constrained waveform and negligible inter-symbol interference. This is achieved by spreading the datum for a single constellation phase point over many unit baud intervals in such a manner that the energy from any given phase-point datum does not interfere with the energy from preceding and following phase-point data at the appropriate baud-interval sampling instants.

The use of Nyquist-type filtration in a transmission circuit produces a filtered signal stream containing a pulse waveform with a spectrally constrained waveform. The degree to which a Nyquist-type pulse waveform is constrained in bandwidth is a function of the excess bandwidth factor, $\alpha$. The smaller the value of $\alpha$, the more the pulse waveform is constrained in spectral regrowth. It is therefore desirable to have the value of $\alpha$ as small as possible. However, as the value of $\alpha$ is decreased, the ratio of the spectrally constrained waveform magnitude to the spectrally unconstrained waveform magnitude is increased. The spectrally unconstrained waveform is the waveform that would result if no action were taken to reduce spectral regrowth. Typical

designs use $\alpha$ values of 0.15 to 0.5. For an exemplary $\alpha$ value of 0.2, the magnitude of the spectrally constrained waveform is approximately 1.8 times that of the unconstrained waveform. This means that, for a normalized spectrally unconstrained waveform magnitude power of 1.0, the transmitter output amplifier must actually be able to provide an output power of 3.24 ($1.8^2$) to faithfully transmit the spectrally constrained waveform. This poses several problems.

When the transmitter output amplifier is biased so that the maximum spectrally unconstrained waveform (1.0 normalized) is at or near the top of the amplifier's linear region, all "overpower" will be clipped as the amplifier saturates. Such clipping causes a marked increase in spectral regrowth, obviating the use of Nyquist-type filtration.

When the transmitter output amplifier is biased so that the maximum spectrally constrained waveform (1.8 normalized) is at or near the top of the amplifier's linear region, the spectrally unconstrained waveform is at only 56 percent (i.e., $\frac{1}{1.8}$) of the amplifiers peak linear power. This results in an inefficient use of the output amplifier.

Also, the biasing of the transmitter output amplifier so that the spectrally constrained waveform is at or near the top of the amplifier's linear region requires that the output amplifier be of significantly higher power than that required for the transmission of a spectrally unconstrained waveform. Such a higher-power amplifier is inherently more costly than its lower-power counterparts.

## SUMMARY OF THE INVENTION

It is an advantage of the present invention that a circuitry and a methodology are provided that allow a transmitter output amplifier to be biased so that the spectrally unconstrained waveform is at or near the top of the amplifier's linear region without incurring clipping of a spectrally constrained waveform.

It is another advantage of the present invention that a circuitry and methodology are provided that allow a spectrally constrained waveform to have approximately the same magnitude as the spectrally unconstrained waveform without effecting a significant increase in spectral regrowth.

It is another advantage of the present invention that a circuitry and methodology are provided which allow a spectrally constrained waveform to be utilized with a continuous transmission scheme.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, thus allowing higher power output for a given output amplifier and a given bandwidth constraint than was previously feasible.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, which allows allowing a lower-power amplifier to be used for achieving given bandwidth constraints than was previously feasible, thus effecting a significant saving in the cost thereof.

These and other advantages are realized in one form by a constrained-envelope digital communications transmitter circuit. The transmitter circuit has a pulse-spreading filter configured to receive a quadrature phase-point signal stream of digitized quadrature phase points and produce a filtered signal stream, which filtered signal stream exhibits energy corresponding to each phase point spread throughout a plurality of baud intervals. The transmitter circuit also has a constrained-envelope generator coupled to the pulse-spreading filter and configured to produce a constrained-

methodology of the present invention may be applied to all forms of constellations. The present invention is especially beneficial when used with constellations having rings of different magnitudes, i.e., amplitude and phase-shift keying (APSK) constellations. This is true because APSK constellations, requiring amplitude modulation of the signal, desirably use linear amplifiers to reproduce that amplitude modulation.

Each phase point **54** in constellation **46** represents a plurality, in this example four, of symbols. The values of the symbols in a given phase point **54** determine the location of that phase point **54** within constellation **46** in a manner well known to those skilled in the art.

Each quadrature phase point **54** may be thought of as having a vector value expressed as I,Q in the Cartesian coordinate system, where I is the in-phase (abscissa) value and Q is the quadrature (ordinate) value of the vector, or expressed as M,$\phi$ in the polar coordinate system, where M is the magnitude and $\phi$ is the phase angle of the vector. In this discussion, the M,$\phi$ designation will be used throughout, as the vector magnitude is the most discussed vector component.

In the exemplary 16-P-APSK constellation **46** of FIG. 3, each phase point **54** resides upon an outer ring **56** or an inner ring **58**. Phase-points **54** residing upon outer ring **56** are outer-ring or maximum-magnitude phase points **60**. That is, outer-ring phase points **60** have a maximum magnitude (maximum value of M) as represented by the radius of outer ring **56**. For purposes of discussion, the magnitudes of outer-ring phase points **60** are normalized to 1.00.

Inner-ring phase points **62**, i.e., those phase points **54** residing upon inner ring **58**, have a lesser magnitude as represented by the radius of inner ring **58**. For the exemplary 16-P-APSK constellation **46** depicted in FIG. 3, the magnitudes of inner-ring phase points **62** may desirably be approximately 0.63 when outer-ring phase point **60** magnitudes are normalized to 1.00.

FIG. 4 depicts a plurality of signal streams, in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2 through 4.

The output of phase mapper **44** is phase-point signal stream **50**. Phase mapper **44** processes one phase point **54** per unit baud interval **64**. That is, phase-point signal stream **50** consists of a series of consecutive phase-point pulses **66**, each of which represents one phase point **54**, whose leading edges are one unit baud interval **64** apart. Those skilled in the art will appreciate that other embodiments of phase-point signal stream **50** are equally valid, that the embodiment utilized is dependent upon the circuitry producing and processing phase-point signal stream **50**, and that the use of other embodiments of this or any other signal stream does not depart from the spirit of the present invent nor the scope of the appended claims.

FIGS. 3 and 4 illustrate a series of twelve exemplary sequential phase points **52**, representative of a random data stream processed by transmitter circuit **22** (FIG.2). These twelve exemplary phase points **52** reside at temporally consecutive locations labeled $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, $t_5$, $t_6$, $t_7$, $t_8$, $t_9$, $t_{10}$, and $t_{11}$. These labels represent sequential integral times at unit baud intervals **64**, i.e., integral-baud times, and indicate the leading-edge times of phase-point pulses **66**. For purposes of simplification within this discussion, any occurrence at time $t_N$ shall be referred to as "occurrence $t_N$". For example, an exemplary phase point **52** occurring at time $t_2$ shall be referred to as phase point $t_2$, and the associated phase-point pulse **66** whose leading edge occurs at time $t_2$

shall be referred to as phase-point-signal pulse $t_2$. In other words, at time $t_2$, phase point $t_2$ is clocked and phase-point-signal pulse $t_2$ begins. One unit baud interval **64** later, at time $t_3$, phase point $t_3$ is clocked and phase-point pulse $t_3$ begins. This process continues indefinitely, with twelve exemplary phase points $t_0$ through $t_{11}$ depicted in FIG. 3 and twelve corresponding phase-point-signal pulses $t_0$ through $t_{11}$ depicted in phase-point signal stream **50** of FIG. 4.

Table 1 below illustrates the magnitudes for phase-point-signal pulses to through $t_{11}$.

TABLE 1

| Phase-Point Pulse Magnitudes | |
| --- | --- |
| Phase-Point-Signal Pulse | Magnitude |
| $t_0$ | Outer-Ring 68 |
| $t_1$ | Inner-Ring 70 |
| $t_2$ | Outer-Ring 68 |
| $t_3$ | Outer-Ring 68 |
| $t_4$ | Inner-Ring 70 |
| $t_5$ | Outer-Ring 68 |
| $t_6$ | Outer-Ring 68 |
| $t_7$ | Outer-Ring 68 |
| $t_8$ | Outer-Ring 68 |
| $t_9$ | Inner-Ring 70 |
| $t_{10}$ | Outer-Ring 68 |
| $t_{11}$ | Inner-Ring 70 |

Phase point $t_0$ is an outer-ring phase point **60**. Phase-point-signal pulse to therefore has an outer-ring magnitude **68**. In like manner, phase point $t_1$ is an inner-ring phase point **62** and phase-point-signal pulse $t_1$ has an inner-ring magnitude **70**.

Phase-point signal stream **50** effects locus **48** through constellation **46**. Locus **48** coincides with the location of each exemplary phase point $t_0$ through $t_{11}$ in turn at unit baud intervals **64**. In FIG. 3, locus **48** is depicted as effecting a minimum distance (straight line) path between adjacent exemplary phase points **52**. Those skilled in the art will appreciate that locus **48** is so depicted solely for the sake of simplicity, and that in actual practice, locus **48** instantly jumps or snaps between exemplary phase points **52** in a discontinuous manner.

FIG. 5 depicts an expanded phase-point constellation **46'** illustrating a locus **72** of a filtered signal stream **74** (FIG. 2) over twelve exemplary sequential phase points **52** in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2 through 5.

In the preferred embodiment, phase-point signal stream **50** passes to the input of a pulse-spreading filter **76**, preferably realized as a Nyquist-type filter, such as a Nyquist, root-Nyquist, raised cosine-rolloff, etc., filter. Pulse-spreading filter **76** filters phase-point signal stream **50** into filtered signal stream **74**, depicted in FIG. 5. In orthogonal frequency division multiplex (OFDM) systems, also known as multitone modulation (MTM) systems, pulse-spreading filter **76** may be implemented using a transmultiplexer or equivalent circuitry.

In accordance with Shannon's theory, well known to those skilled in the art, pulse-spreading filter **76** produces at least two (only two in the preferred embodiment) output filtered-signal pulses **78**, i.e., complex samples of filtered signal stream **74**, for each input phase-point pulse **66** received. This is demonstrated in FIG. 4 where filtered signal stream **74** possesses two filtered-signal pulses **78** per unit baud interval **64**. In the preferred embodiment, filtered-signal pulses **78**

consist of alternating on-time pulses 80, i.e., samples of filtered signal stream at integral unit baud intervals 64, and off-time pulses 82, i.e., samples of filtered signal stream 74 between integral unit baud intervals. In effect, filtered signal stream 74 is made up of two interleaved data streams, an on-time signal stream 84 and an off-time signal stream 86.

On-time signal stream 84 is substantially a version of phase-point signal stream 50, wherein each phase-point pulse 66 has been reduced in duration from one unit baud interval 64 to a half-unit baud interval 88 to become on-time pulse 80 while maintaining substantially the same relative leading-edge time. That is, filtered-signal pulse to has substantially the same magnitude and substantially the same leading edge time as phase-point pulse to with approximately one-half the duration. Of course, those skilled in the art will appreciate that signal streams 74 and 84 may be delayed from signal stream 50 by a delay imposed by filter 76.

The generation of both on-time pulses 80 and off-time pulses 82 by pulse-spreading filter 76 effectively populates expanded constellation 46' (FIG. 5) with on-time phase-points 90 (circles) and off-time phase points 92 (squares). The original phase points 54 of constellation 46 (FIG. 3), i.e., the phase points carrying the intelligence to be communicated by transmitter circuit 22, are on-time phase points 90 of expanded constellation 46'.

Added to expanded constellation 46' are off-time phase points 92, with each off-time phase-point 92 occurring approximately midway in time between consecutive on-time phase points 90. Therefore, exemplary sequential phase points 52 become exemplary filtered phase points 94. Exemplary filtered phase points 94 are made up of alternating exemplary on-time filtered phase points 96 and exemplary off-time filtered phase points 98, and reside at temporally consecutive locations labeled $t_0$, $t_{0.5}$, $t_1$, $t_{1.5}$, $t_2$, $t_{2.5}$, $t3$, $t_{3.5}$, $t_4$, $t_{4.5}$, $t_5$, $t_{5.5}$, $t_6$, $t_{6.5}$, $t_7$, $t_{7.5}$, $t_8$, $t_{8.5}$, $t_9$, $t_{9.5}$, $t_{10}$, $t_{10.5}$, and $t_{11}$, In FIG. 5, exemplary on-time filtered phase points 96 are located at integral-baud times ($t_0$, $t_1$, $t_2$, etc.), whereas exemplary off-time filtered phase points 98 are located at fractional-baud (non-integral-baud) times ($t_{0.5}$,$t_{1.5}$, $t_{2.5}$, etc.).

The generation of off-time phase points 92 approximately midway in time between consecutive on-time phase points 90 causes filtered signal locus 72 to effect excursions having local peak magnitudes 99 greater than outer-ring magnitude 68. Such excursions occur because the immediate position of locus 72 at any given instant in time is not only a result of those phase points 54 proximate that position, but of a plurality of phase points 54 both preceding and following that instant in time. That is, in the preferred embodiment, the determination of the position of locus 72 at time $t_{2.5}$ (i.e., coincident with off-time phase point $t_{2.5}$) is determined not only by the positions of phase points $t_2$ and $t_3$, but by the positions of numerous phase points 54 preceding phase point $t_{2.5}$ (i.e., phase points $t_2$, $t_{1.5}$, $t_1$, $t_{0.5}$, etc.) and the positions of numerous phase points 54 following phase point $t_{2.5}$ (i.e., phase points $t_3$, $t_{3.5}$, $t_4$, $t_{4.5}$, etc.)

This phenomenon is illustrated in FIG. 6, which depicts a pair of Nyquist-type datum bursts 100 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2, 4, 5, and 6.

In the preferred embodiment, pulse-spreading filter 76 is realized as a Nyquist-type filter. Therefore, when a single phase-point pulse 66 is filtered by pulse-spreading filter 76, that single pulse 66 is transformed into a Nyquist-type datum burst 100 extending over a plurality of unit baud intervals 64. It is a property of Nyquist-type filters that

datum burst 100 attains a datum-burst peak value 102 (i.e., a local peak magnitude) at the primary sampling time of the specific phase-point pulse 66 (i.e., at time $t_2$ for phase-point pulse $t_2$), and attains a zero datum-burst value 104 (i.e., is equal to zero) at integral unit baud intervals 64 preceding and following peak datum-burst value 102 (i.e., at times ..., $t_{-1}$, $t_0$, $t_1$, and $t_3$, $t_4$, $t_5$, ..., for phase point pulse $t_2$). In this manner, the energy of each pulse 78 is spread over a plurality of baud intervals 64 preceding and following the clocking instant (time $t_2$).

FIG. 6 illustrates Nyquist-type datum bursts 100 for phase-point pulses $t_2$ and $t_3$, with datum burst $t_2$ depicted as a solid line and datum burst $t_3$ depicted as a dashed line. As an example, it may be seen from FIG. 6 that at time $t_2$ the value of datum burst $t_2$ is peak datum-burst value 102. At every other time separated from time $t_2$ by an integral number of unit baud intervals 64, the value of datum burst $t_2$ is zero. An analogous condition occurs for datum burst $t_3$.

The value of locus 72 is, at each moment in time, the sum of all datum bursts 100 at that moment. In the simplified two-datum-burst example of FIG. 6, locus 72, depicted by a dotted line, is the sum of datum burst $t_2$ and datum burst $t_3$. Since datum bursts $t_2$ and $t_3$ are zero at each integral time $t_N$ except times $t_2$ and $t_3$, the value of locus 72 is also zero except at times $t_2$ and $t_3$, where it assumes the peak values of datum bursts $t_2$ and $t_3$, respectively.

The value of locus 72 at any instant in time between integral-baud times is the sum of the values of all datum bursts 100 at that instant. For example, in FIG. 6 where only two datum bursts 100 are considered, locus 72 has a value at time $t_{2.5}$ that is the sum of the values of datum bursts $t_2$ and $t_3$ at time $t_{2.5}$. Since datum bursts $t_2$ and $t_3$ both have significant positive values at time $t_{2.5}$, locus 72 has a value significantly greater than the maximum values of either datum burst $t_2$ or datum burst $t_3$.

Since locus 72 describes the sum of all datum bursts 100, locus 72 is a function of the shape of the curves (FIG.6) describing those datum bursts 100. That is, locus 72 is a function of a filtered-signal peak magnitude component of a filtered-signal complex digital value at any given point. The shape of the datum-burst curve is a function of the excess bandwidth factor, $\alpha$, a design property of pulse-spreading filter 76. The smaller the value of $\alpha$, the more locus 72 may rise above the peak datum burst values 102 of adjacent datum bursts 100. Typical designs of pulse-spreading filters 76 use $\alpha$ values of 0.15 to 0.5. For like-valued adjacent phase points 54 and an $\alpha$ value of 0.2, a maximum excursion magnitude 105 (i.e., the potential local peak magnitude 99 of locus 72) is approximately 1.8 times the value of the maximum phase-point magnitude. That is, the magnitude of the constrained envelope is approximately 1.8 times that of the unconstrained envelope. In the preferred embodiment depicted in FIGS. 3, 4, and 6, on-time phase points $t_2$ and $t_3$ are both outer-ring phase points 60 having a normalized outer-ring magnitude 68 of 1.00. Therefore, off-time phase point $t_{2.5}$ may have a normalized maximum excursion magnitude 105 of 1.8. This implies that transmitter circuit 22, to faithfully transmit phase point $t_{2.5}$ without excessive distortion, and without the benefit of the present invention, would require an output power of 3.24 ($1.8^2$) times the power required to transmit phase point $t_2$ or $t_3$, which are representative of the highest magnitude intelligence-carrying phase points 54. This represents an inefficient use of available power.

The following discussion refers to FIGS. 2, 4, and 5.

Off-time signal stream 86, a portion of filtered signal stream 74, passes from an output of pulse-spreading filter 76

dent with said difference pulses of said difference signal stream, and wherein, when ones of said difference pulses have said first-polarity difference-pulse values, said coincident error pulses have error-pulse values substantially equal to said first-polarity difference-pulse values, and when ones of said difference pulses have said second-polarity difference-pulse values, said coincident error pulses have error-pulse values substantially equal to zero; and

a second Nyquist-type filter coupled to said discriminator and configured to produce said constrained-bandwidth error signal stream.

**25.** A digital-communications transmitter circuit as claimed in claim **24** wherein said transmitter circuit additionally comprises:

a convolutional encoder coupled to said binary data source and configured to produce an encoded signal stream; and

an interleaver coupled to said convolutional encoder and configured to produce an interleaved signal stream by temporally decorrelating said encoded signal stream.

**26.** A digital-communications transmitter circuit as claimed in claim **24** wherein:

said filtered signal stream is a quadrature signal stream having a locus that passes proximate one of said phase

points of said phase-point constellation at integral unit baud intervals;

said first filtered-signal data stream comprises on-time samples of said filtered signal stream, each of said on-time samples occurring substantially coincidentally with said passage of said filtered signal locus proximate one of said phase points of said phase-point constellation; and

said second filtered-signal data stream comprises off-time samples of said filtered signal stream wherein each of said off-time samples occurs between adjacent ones of said on-time samples.

**27.** A digital-communications transmitter circuit as claimed in claim **26** wherein each of said off-time samples occurs substantially midway between adjacent ones of said on-time samples.

**28.** A digital-communications transmitter circuit as claimed in claim **23** additionally comprising an interleaver coupled to said binary data source and configured to provide an interleaved signal stream.

**29.** A digital-communications transmitter circuit as claimed in claim **23** wherein said constellation is an amplitude and phase shift keying constellation.

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